HCAT MEETING
16 March 2005

In Search of the Holy Grail (of EHC Alternatives)

Joe Kolek

AFRL/MLSC

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
16 MAR 2005		**00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
In Search of the Holy Grail (of EHC Alternatives)	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory,AFRL/MLSC,Wright Patterson AFB,OH,45433**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
25th Replacement of Hard Chrome and Cadmium Plating Program Review Meeting, March 15-17, 2005, Greensboro, NC. Sponsored by SERDP/ESTCP.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**46**	

Quests Underway

- Non-Line of Sight (NLOS) Hard Chrome Alternatives
- Advanced Non-Line of Sight (ANLOS) Hard Chrome Alternatives
- Alternative Spray Process Coatings Evaluation
- Metal-Coated Particles Evaluation
- Effects of Chemicals on HVOF Coatings Follow-up

Non-Line of Sight (NLOS) Hard Chrome Alternatives

NLOS Hard Chrome Alternatives

- High Velocity Oxygen Fuel (HVOF) thermal spray of Tungsten Carbide-Cobalt (WC-17Co) is being transitioned by the AF as the primary alternative to Electrolytic Hard Chrome (EHC) plating
- HVOF is a line of sight process unable to accommodate internal diameters, blind holes and complex shapes
- Non-Line of Sight (NLOS) plating requirements are 20 – 40% of the ALC workload and an alternative to EHC for these applications is required if the use of chrome plating is to be minimized / eliminated

NLOS Hard Chrome Alternatives

- Potential alternatives search and initial down-selection
- Screening testing of 10 candidates
  - **Least costly testing done first**
  - **OC-ALC provided EHC coatings**
  - **Each vendor applied its own product in order to eliminate any chance of processing anomalies**
    - .005” thick coatings were requested
    - Coatings ground to .003”
    - 2 coating variations
      - As deposited
      - Baked at 375°F/24 hrs (Standard hydrogen relief bake)

NLOS Hard Chrome Alternatives

Initial Screening Testing

Adhesion: ASTM B571 Mandrel & Vise Bend tests

Hardness: HVN determination w/ 75 gram indenter

Profilometry: Smoothness / leveling ability of coating

Chemical composition: No unacceptable constituents

Quality: Visual analysis IAW Fed Spec QQ-C-320B

Taber wear index: Weight loss per 1000 cycles

- **Selected the 4 best processes for further evaluation**

NLOS Hard Chrome Alternatives

Niplate 700 by Surface Technology

- Electroless Nickel (95%) – Phosphorous (5%) with silicon carbide particles

UltraCem by Universal Chemical

- Electroless Nickel (95%) – Boron (5%) that forms crystalline clusters of nickel boride

Nanon 9 by Nanon Technologies

- Electrolytic Nickel (50-70%) – Cobalt (30-50%) that forms nanocrystalline microstructure

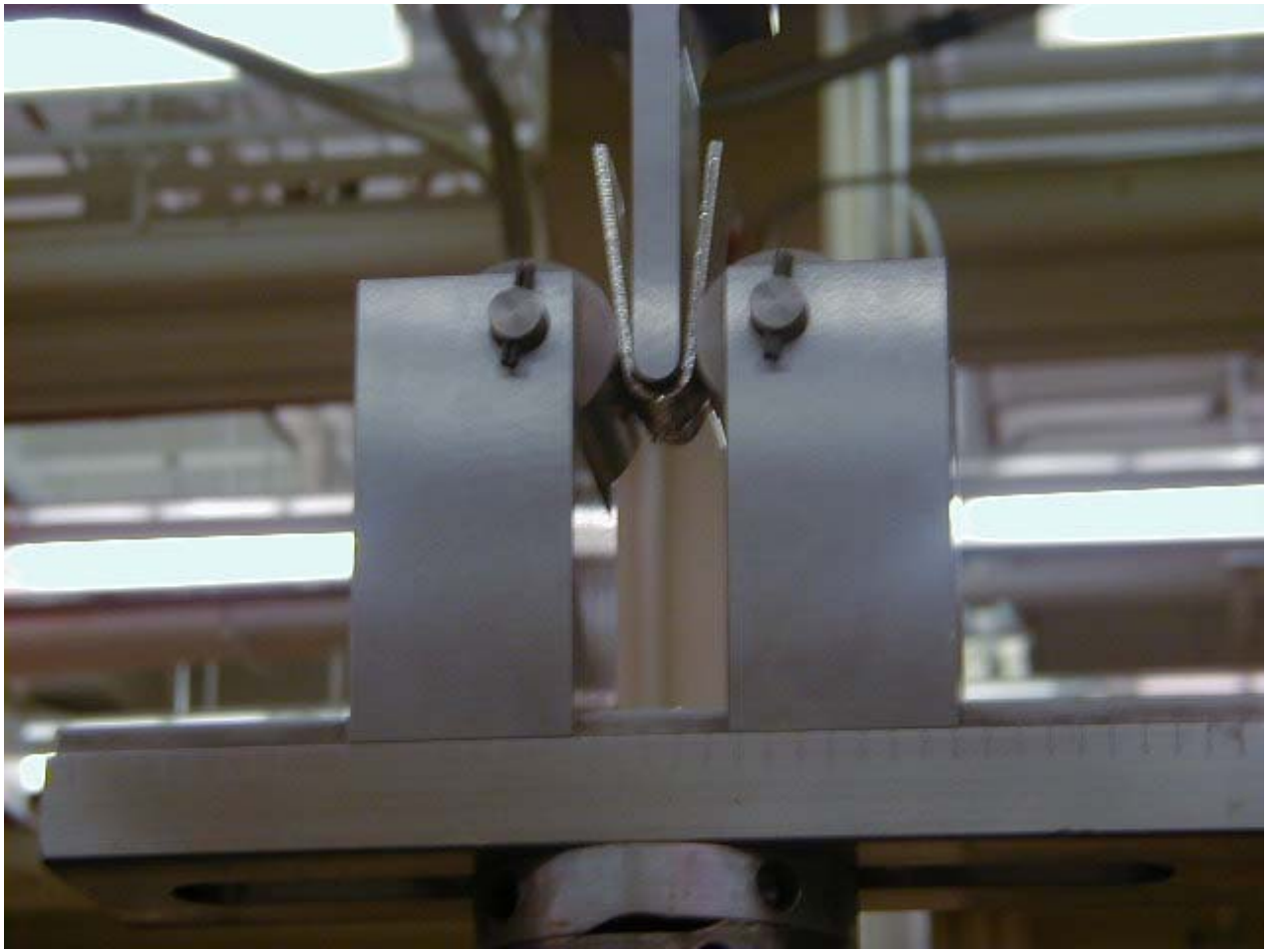
NiCom by US Chrome

- Electrolytic Nickel w/ silicon carbide particles

NLOS Hard Chrome Alternatives

Mandrel Bend Adhesion Testing

Mandrel radius 4 X thickness of 4130 steel substrate (0.090”)

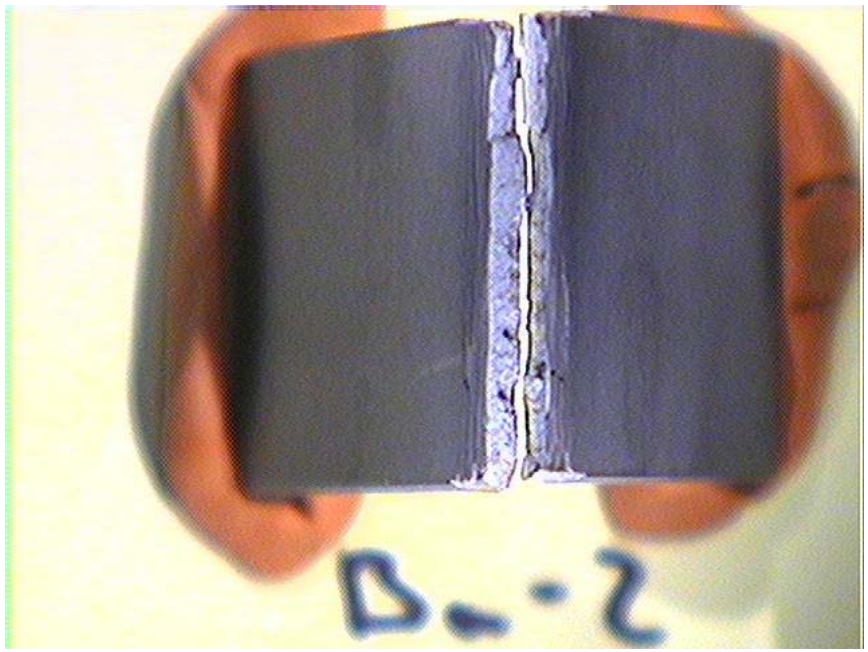


NLOS Hard Chrome Alternatives

Typical Mandrel Bend Test Results

ASTM B571 Section 3.1

EHC; Nanon 9; Unbaked UltraCem

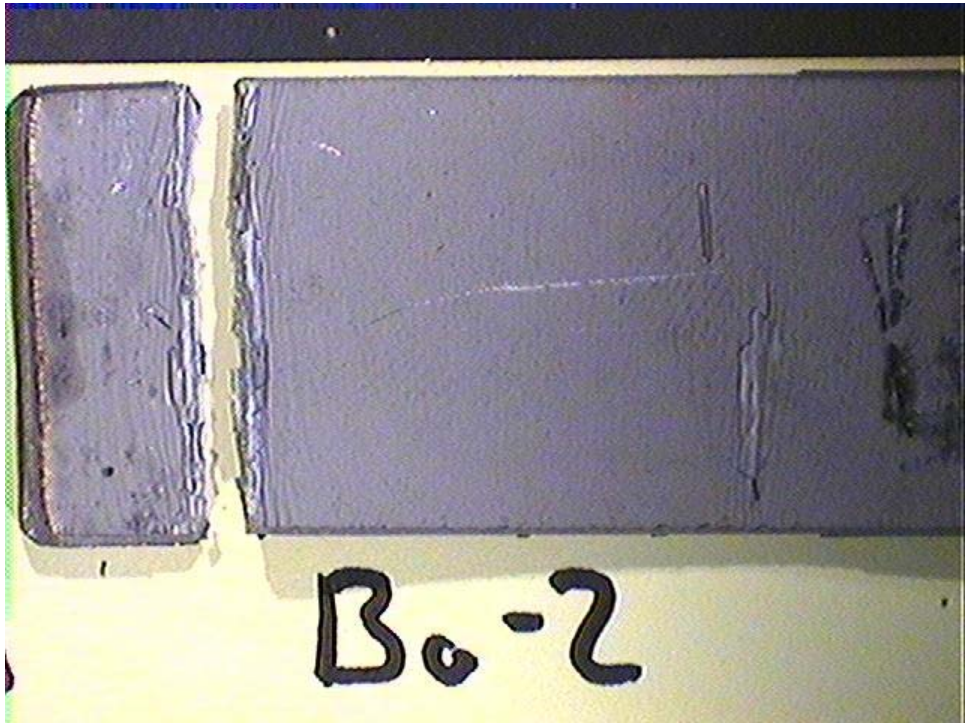


Niplate 700; NiCom; Baked UltraCem

NLOS Hard Chrome Alternatives

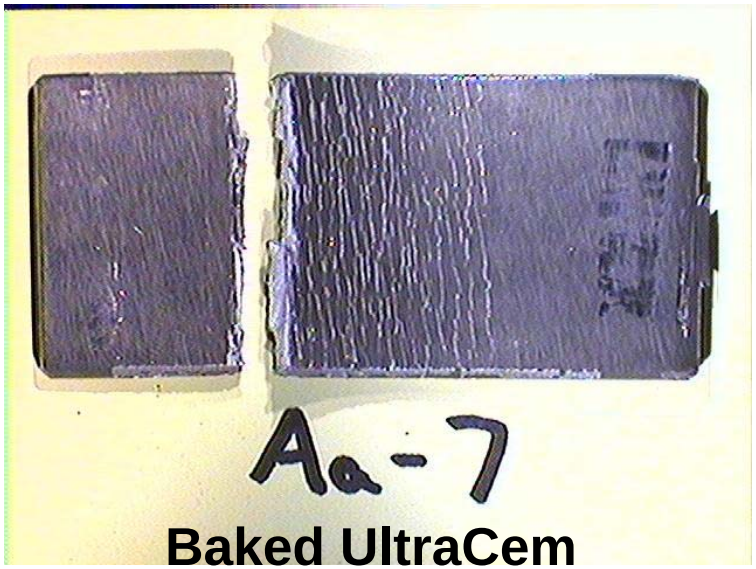
Typical Vice Bend Test Results

ASTM B571 Section 3.2



Niplate 700

Unbaked UltraCem



Baked UltraCem

NLOS Hard Chrome Alternatives

Initial Screening Test Results

	Niplate 700	UltraCem	Nanon 9	NiCom
Adhesion EHC Pass 3.1 Fail 3.2	As deposited & Baked Pass	As deposited: Pass 3.1 Fail 3.2 Baked: Pass	As deposited & Baked Pass	As deposited: Pass Baked: Pass 3.1 Fail 3.2
Hardness EHC = 895 HVN	781 (As deposited) 939 (Baked)	872 (As deposited) 910 (Baked)	934 (As deposited) 927 (Baked)	434 (As deposited) 541 (Baked)
Profilometry	Acceptable	Acceptable	Acceptable	Acceptable
Composition	As Claimed	As Claimed	As Claimed	As Claimed
Quality	Acceptable	Acceptable	Acceptable	Acceptable
Taber Wear Index EHC = 2.2 (10 or less acceptable)	2.8 (As deposited) 2.6 (Baked)	9.8 (As deposited) 14.0 (Baked)	12.0 (As deposited) 10.8 (Baked)	9.7 (As deposited) 6.0 (Baked)

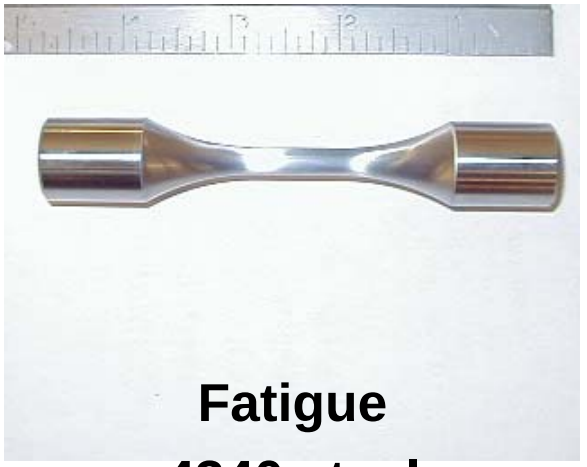
NLOS Hard Chrome Alternatives

- **Final Screening Testing**
  - **Corrosion:** B-117 (1000hrs) and Electrochemistry Eval.
  - **Fatigue:** @185 ksi, R=.1, 10 cycles / sec until failure
  - **Hydrogen Embrittlement:** ASTM F519
  - **Block-on-Ring Wear:** ASTM G77-98
  - **Grindability determination**
  - **Strippability determination**

NLOS Hard Chrome Alternatives Test Specimen

Corrosion

4130 steel



Fatigue

4340 steel

Hydrogen Embrittlement

4340 steel

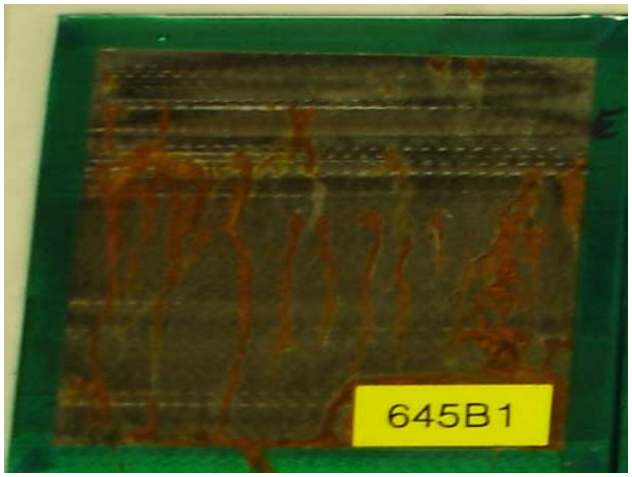
Block-on-Ring Wear

Both 4340 steel

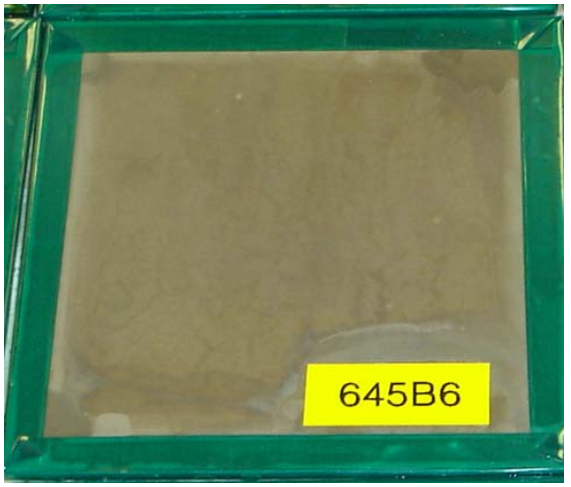
Only block is coated

NLOS Hard Chrome Alternatives
After 20 hrs

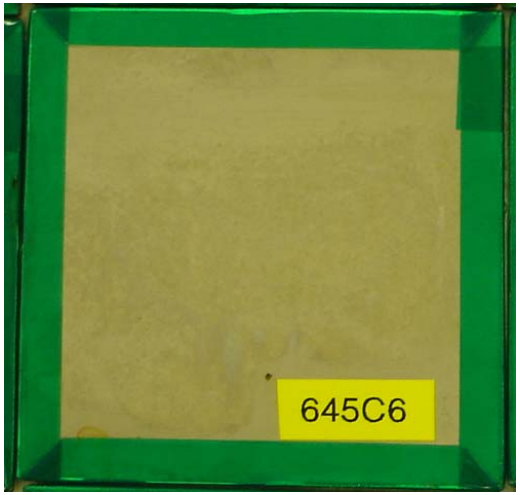
UltraCem



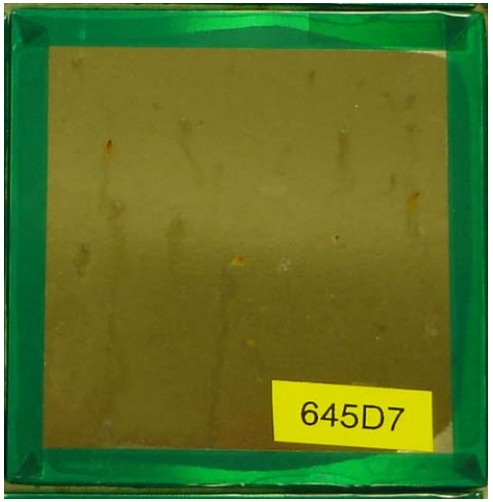
Niplate 700 Ground



Niplate 700 Unground



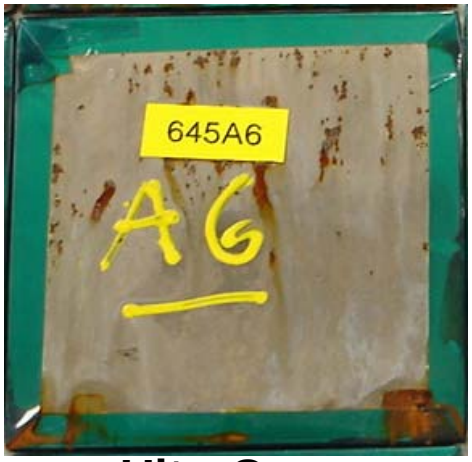
NiCom



Nanon 9

EHC

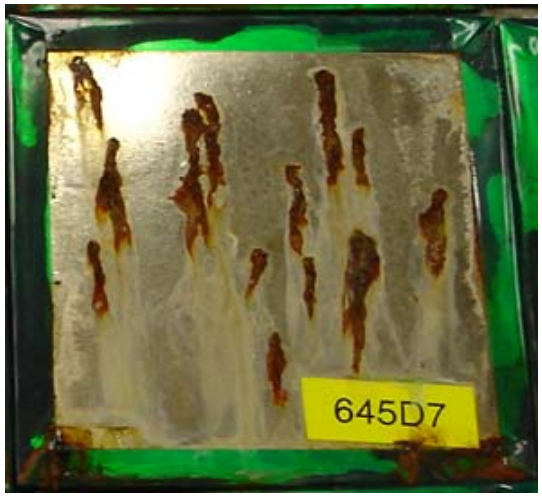
NLOS Hard Chrome Alternatives
After 1000 hrs



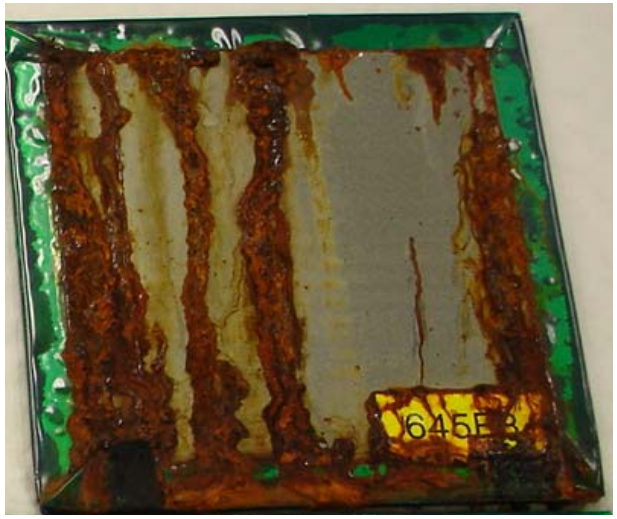
UltraCem
Unground

Niplate 700
Unground

NiCom



Nanon 9



EHC

Electrochemistry Evaluation

- To evaluate the electrochemical corrosion resistance of EHC and the alternative coatings in a mild (3.5%) NaCl solution.
- High Impedance (I **Z** I) is desirable. Indicates coating is better barrier to the flow of electrons. This metric is the most indicative of the coating performance expected in a field application.
- Difference between **E** corr (equivalent to Open Circuit Potential) and **E** pit (Pitting Potential) indicates voltage required to induce pitting. Higher difference indicates greater corrosion resistance.
- Low Corrosion Current (**I** corr) is desirable. Indicates that a larger current density is required to cause coating failure.
- I **Z** I primary metric. Use Δ between **E** corr and **E** pit if coatings have same magnitude of I **Z** I. If needed (it wasn't), use **I** corr to further distinguish between performances of two coatings.

Electrochemistry Evaluation

- **I Z I** : EHC = **3.66 x 10^5** ohm-cm ~ Niplate 700 = **3.55 x 10^5** ohm-cm
- **I Z I** : NANON 9 = **1.01 x 10^5** ohm-cm
- **I Z I** : UltraCem and NiCom values more than order of magnitude less
- Difference between **E** corr & **E** pit : EHC = **875**mV NiPlate 700 = **200**mV
  NANON 9 = **80** mV

Result of overall weighted average rankings

#1: EHC

#2: NiPlate 700 (a close second to EHC)

#3: NANON 9

#4 / #5 : UltraCem and NiCom (clearly inferior to the other alternatives)

NLOS Hard Chrome Alternatives

Final Screening Test Results

	Niplate 700	UltraCem	Nanon 9	NiCom
B117 Corrosion Testing	#3 As good as EHC	#2 As good as EHC	#4 As good as EHC	#1 As good as EHC
Electrochemistry Evaluation EHC is best	#1 Almost as good as EHC	#3 Significantly Inferior	#2	#4 Significantly Inferior
Fatigue EHC: 5801 - 7661 cycles to failure	Pass Fatigue Debit < EHC 42000 - 93000 cycles	Pass Fatigue Debit < EHC 7951 - 13871 cycles	Fail Fatigue Debit > EHC 1020 - 1738 cycles	Pass Fatigue Debit < EHC 19587 - 124367 cycles
Hydrogen Embrittlement EHC (baked): Pass	Pass (as deposited and baked)	Pass (as deposited and baked)	Pass (as deposited and baked)	Fail: as deposited Pass: baked
Block-on-Ring Testing EHC scar depth: 0.88 mil	0.90 mil (as deposited) 0.59 mil (baked)	2.49 mil (as deposited) 2.57 mil (baked)	2.62 mil (as deposited) 4.60 mil (baked)	3.21 mil (as deposited) 3.19 mil (baked)
EHC Coefficient of Friction: 0.7	0.7 (as deposited) 0.7 (baked)	0.8 (as deposited) 0.9 (baked)	0.7 (as deposited) 0.8 (baked)	0.6 (as deposited) 0.7 (baked)
Grindability	I Difficult to grind	Acceptable (coating on corrosion panels cracked)	Best surface finish	Acceptable
Strippability: 3 mil coating EHC: 1hr w/50% HCL	Acceptable 3 - 4 hrs w/ Nistrip R501	Acceptable 3 - 4 hrs w/ Nistrip R501	Acceptable 3 - 4 hrs w/ Nistrip R501	Acceptable 3 - 4 hrs w/ Nistrip R501

NLOS Hard Chrome Alternatives

- **Niplate 700: Best Alternative**
- **Hardness and Wear performance comparable to EHC**
- **Best adhesion test performance**
- **Best electrochemistry evaluation results**
- **Corrosion test performance as good as EHC**
- **Passed hydrogen embrittlement and fatigue testing**
- **Optimum grinding technique needs to be determined**

NLOS Hard Chrome Alternatives

Validation Testing of NiPlate 700

- Establish coating capability at NDCEE
- Coat and test specimen to ensure that performance of coating is equivalent to that applied by Surface Technology
- Demonstrate NiPlate 700 can plate components with NLOS requirements

ALC Implementation Plan

- Identify facility requirements and cost to establish plating capability
- Facilitate transition

Advanced Non-Line of Sight (ANLOS) Hard Chrome Alternatives

Advanced Non-Line of Sight (ANLOS) Hard Chrome Alternatives

- Non-chrome, non-nickel containing coatings
- Processes should fit ALC production environment
- Available and emerging technologies considered
  - Nano structured and nano material coatings are included
- Technical approach similar to the NLOS project
- Alternatives identification phase and initial down-selection completed
- STATUS: Preparation of Specimen For Screening Testing Is Underway

Advanced Non-Line of Sight (ANLOS) Hard Chrome Alternatives

- Integran Technologies electroplated Co-P*
- Surface Technology electroless Co-P w/ diamond**
- Surface Technology electroless Co-B w/ diamond**
- Zinex Corp. NR 2000 electroplated Co-W
- Whyco Technologies electroplated Co-SiC
- Boeing Corp. electroplated Co-P

* Nano structured as deposited

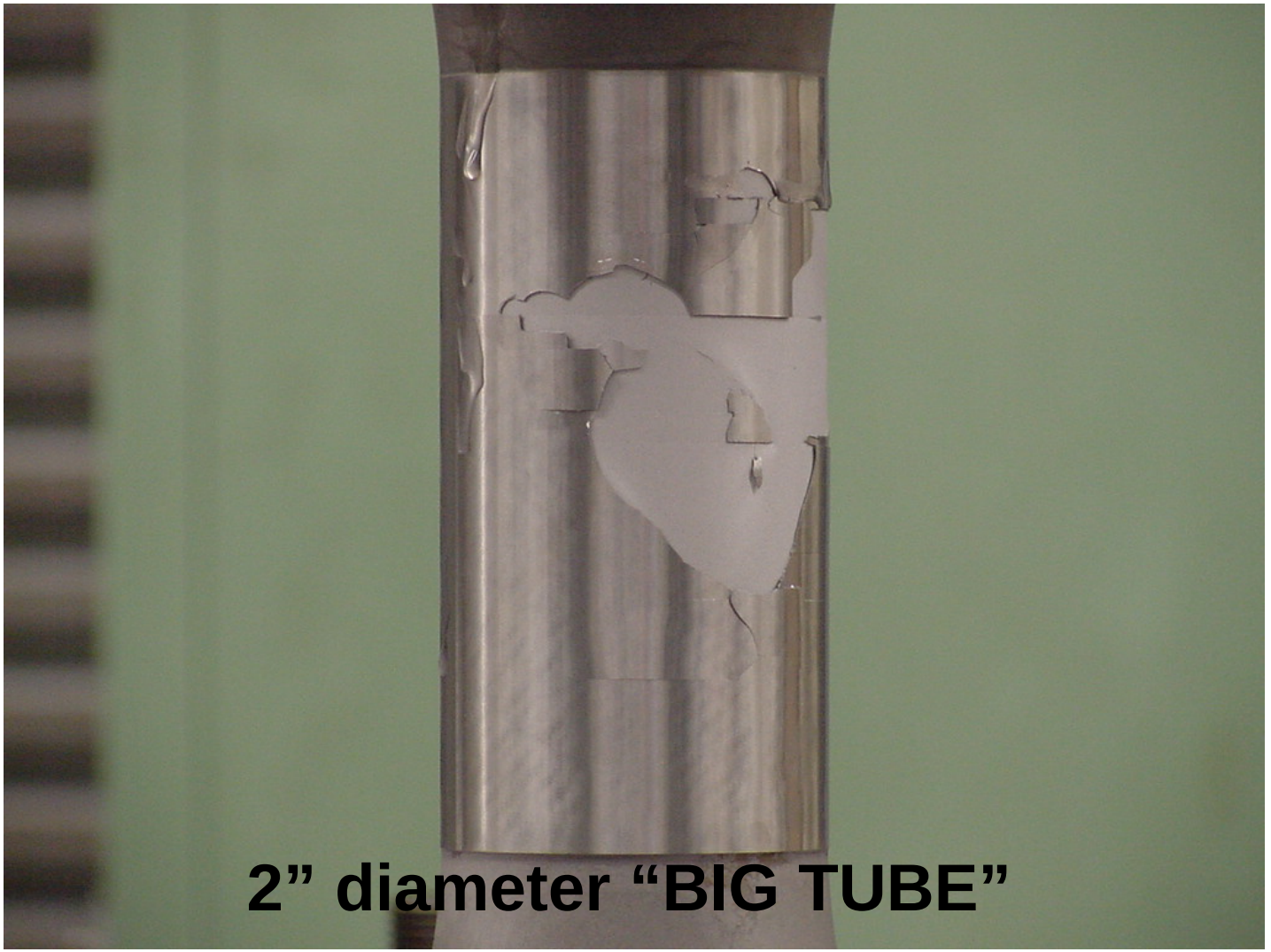
** Could be deposited as an amorphous microstructure and converted to Nano-structure by heating

Alternative Spray Process Coatings Evaluation

Alternative Spray Process Coatings Evaluation

- HVOF WC-17Co coatings will crack, spall and delaminate when the 4340, Rc 53, High Strength Steel substrate is stressed greater than 180 ksi
- This “coating integrity” issue could limit the use of HVOF WC-17Co coatings for high stress applications
- Spray processes that operate at a lower temperature than HVOF may provide a more ductile WC-17Co coating

.005” thick HVOF WC-17Co coating
180 ksi @ R=-.33



2” diameter “BIG TUBE”

After only 5 cycles

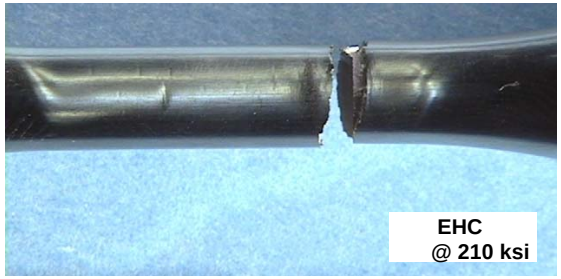
Alternative Spray Process Coatings Evaluation

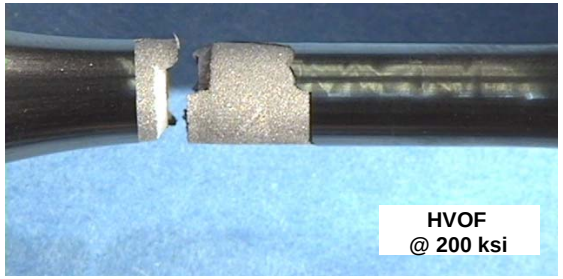
- Previously conducted a limited evaluation of WC-17Co coatings applied by 5 alternative processes
- Only two coating processes showed promise
  - **Activated Combustion – High Velocity Air Fuel (AC-HVAF) developed by Unique Coat Technologies, Corp.**
    - **Particles preheated and sprayed below their melting point**
  - **Kinetic Metallization (KM) developed by Inovati, Corp.**
    - **Particles sprayed at room temperature**
    - **Helium used for propellant**

Alternative Spray Process Coatings Evaluation

Results of Limited Coating Integrity Evaluation

Unique Coat Technologies AC-HVAF coated specimen after fatigue testing (.1 stress ratio, 25 Hz)





AC-HVAF @ 185 ksi **AC-HVAF @ 220 ksi**

3 mil thick WC-17Co coating on 4340 steel

Alternative Spray Process Coatings Evaluation

WC-17Co applied by

Unique Coat (AC-HVAF) and **Inovati (KM)**

compared to

HVOF WC-17Co applied by OO-ALC

- Coating Integrity Fatigue Testing W/ Big Tubes
- B117 Corrosion Testing
- Metallurgical Analysis

Alternative Spray Process Coatings Evaluation

- **"BIG TUBE" Coating Integrity Fatigue Testing**
  - **2" diameter, 4340, R_c 53, smooth gage specimen**
  - **4" long coating patch, ground to .003" and .010"**
  - **Stress Ratio (R) = -.33 & -1 @ .125 Hz**
  - **Start @ 140 ksi, increase 10 ksi every 20 cycles**
  - **Photo will be taken every cycle; NDI as required**
  - **Acoustic emission used to determine acoustic event onset, frequency, magnitude and stress state of the specimen during these events**

Alternative Spray Process Coatings Evaluation

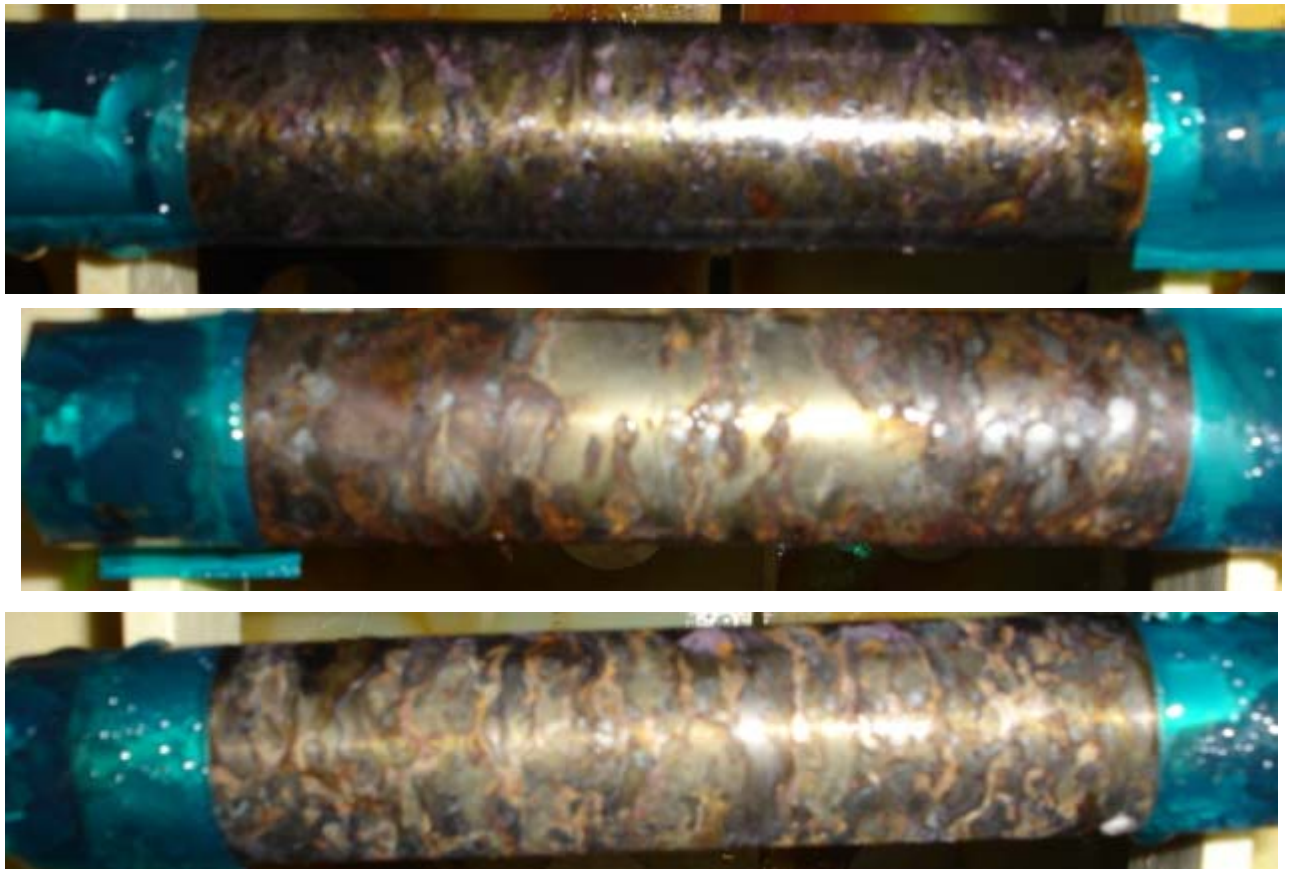
- **B117 Corrosion Testing**
  - 1” diameter X 6” long 4340, R_c 53 Bars
  - 5” long coating patch, ground to .003” and .010”
  - Test for 1000 hrs
  - Photographs & visual evaluation at least every 100 hrs

- **Metallurgical Analysis**
  - Carbide distribution must be uniform
  - Interface contamination not > 10%
  - Cracks or delaminates should not exist
  - Voids/oxides not > 1%, no voids > .002”
  - Unmelted particles are not acceptable

Alternative Spray Process Coatings Evaluation

1000hrs of Corrosion Testing

- **No appreciable difference in performance between KM, AC-HVAF and HVOV WC-17Co coatings**



Alternative Spray Process Coatings Evaluation

Preliminary Integrity Test Data

Type	Thickness	R	Accoustic Emission	Max Stress (ksi)	Remarks
OO-ALC HVOF (2)	.003"	-1	Events began at 150 ksi and continued for every cycle above 160 ksi	220	cracked / spalled at end of coated region @ 170 ksi. Remainder of coating intact
				220	coating intact
HVOF (3)	.010"	-1	Events began with initial cycling and continued to coating failure	160	small spalled area that became large by 180 ksi
				160	coating cracked / spalled
				180	coating cracked / spalled
UniqueCoat AC-HVAF	.003"	-1	Few events with initial cycling and very few afterwards	220	coating intact
AC-HVAF (3)	.010"	-1	Few events with initial cycling and very few until coating failure or test completion	200	coating cracked / spalled
				220	coating intact
				220	coating intact
Inovati KM	.003"	-1	Multiple events with initial cycling and continued to test completion	220	coating cracked / spalled at ends of coated region @ 160 ksi. remainder of coating intact
KM (2)	.010"	-1	Multiple events with initial cycling	160	immediate cracking / spalling (started @ 160 ksi)
				140	immediate cracking / spalling
EHC	.003"	-1	Singluar event upon initial cycling, No events until the big bang	220	coating intact specimen failed 16th cycle @ 220 ksi
EHC	.010"	-1	Multiple events starting @ 180 ksi and continuing to test completion	220	coating intact

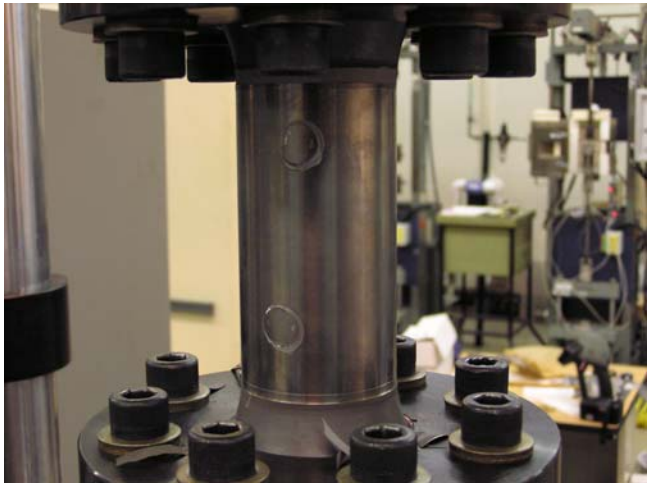
Alternative Spray Process Coatings Evaluation

Coating Integrity Test Setup

Alternative Spray Process Coatings Evaluation

OO-ALC HVOF

.003”



20 cycles @ 220 ksi

.010”

4 cycles @ 160 ksi

Alternative Spray Process Coatings Evaluation

UniqueCoat AC-HVAF

.003”

20 cycles @ 220 ksi

.010”

3 cycles @ 200 ksi

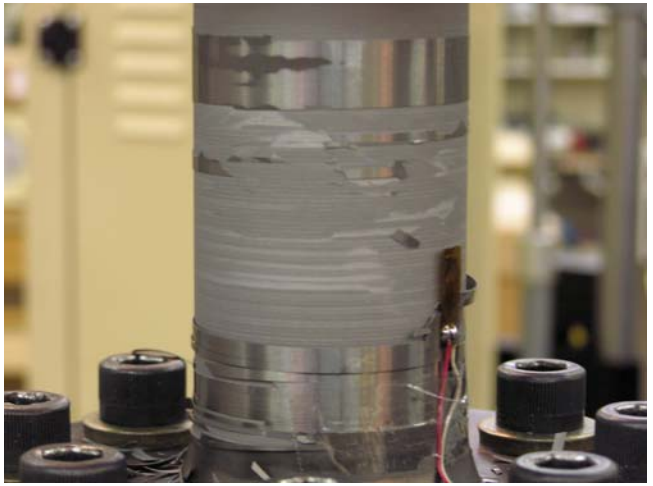
Alternative Spray Process Coatings Evaluation

Inovati KM

.003”

20 cycles @ 220 ksi

.010”

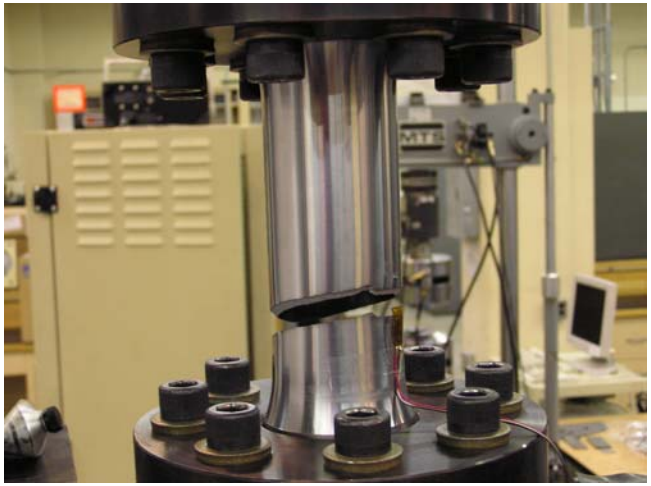


3 cycles @ 140 ksi

Alternative Spray Process Coatings Evaluation

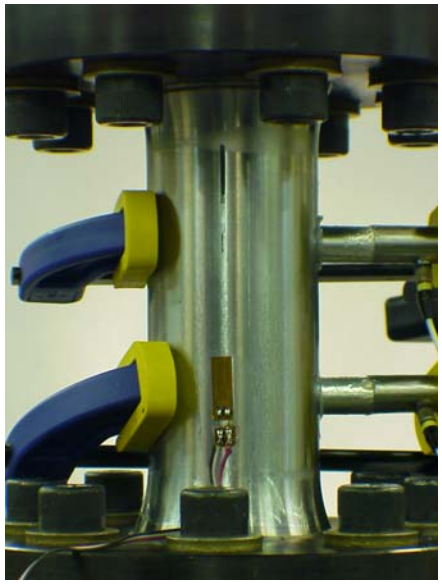
Hohman EHC

.003”



16 cycles @ 220 ksi

.010”



20 cycles @ 220 ksi

Metal-Coated Particles

Proof of Concept Evaluation

Metal-Coated Particles Evaluation

Plating WC particles of HVOF WC-17Co powder, may improve coating ductility and enhance integrity at higher stresses

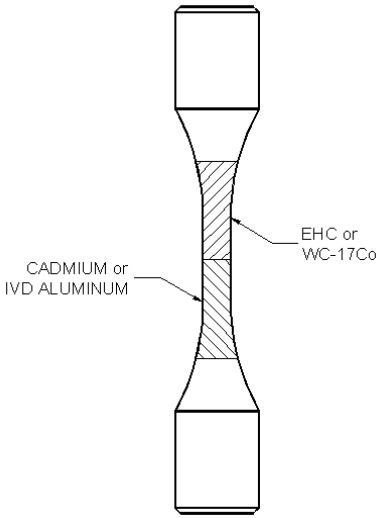
- Federal Technology Group nickel plated WC particles as small as 5 microns in diameter
- Cincinnati Thermal Spray is presently coating the specimen using Ogden ALC HVOF spray parameters.
- AFRL/MLSC provided ¼" diameter, 4340 steel, Rc53 fatigue specimen and will evaluate coating microstructure and integrity
- Coating with cobalt preferred, but too costly for this evaluation
- If warranted, a follow-on project is planned to evaluate the integrity of WC-Co coatings with cobalt plated WC particles

Effects of Chemicals on HVOF Coatings

Follow-up

Testing Approach

¼” diameter, 4340 steel, Rc53, smooth gage specimen



Duplex coated specimen

- ½ coated with **WC-17Co**, ground to .003”
- **Other** ½ coated with **IVD aluminum** or **cadmium**

or

- ½ coated with **EHC**, ground to .003”
- **Other** ½ coated with **IVD aluminum** or **cadmium**

Testing Approach

- Specimen exposed to chemicals while subjected to a constant stress of 180 ksi
- Specimen wetted with chemical every 24 hrs
- 150 hrs without failure was considered passing
- Testing stopped after 196 hours

Testing Approach

Test Set-up

- **6 chemicals**
  - **Type III cleaner** - **Aircraft deicer** - **Paint stripper**
  - **Type IV cleaner** - **Runway deicer** - **Decontaminant**

Testing Results

- **100%** of **55** EHC / IVD alum specimen passed
- **96%** of **28** EHC / cadmium specimen passed
- **92%** of **12** uncoated specimen passed
- **50%** of **48** WC-17Co / IVD alum specimen passed
- **19%** of **16** WC-17Co / cadmium specimen passed

- WC-17Co coatings cracked when stressed to 180 ksi
- Specimen **failed in the WC-17Co region**

Follow-on Testing

- WC-17Co / cadmium coated specimen
  Distilled water (pH 5.26): 1 out of 4 passed
  Rain water (pH 6.02): 3 out of 4 passed
- EHC / cadmium coated specimen
  Distilled water: 3 out of 3 passed
  Rain water: 3 out of 4 passed

- STATUS: Project Completed